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Introduction

Several research areas are evolving in the investigation of nonlinear optics which involve nonlinear partial differential equations. The recent development of femtosecond light sources in the visible and near infrared region makes possible the exploration of new phenomena on ultrashort time scales. Research into this area is significant because it may guide experiments into areas of interest in nonlinear optics; such as, new short pulsed solitons, new femtosecond switches or novel femtosecond lasers.

There is considerable practical interest in all-optical devices. Optical switching is utilized in optical communications and information processing. Of particular interest is high fidelity for good cascadability. Another important consideration is high data rates. This requires shorter pulses. Therefore a greater understanding of short pulse information processing is of growing interest.

It is now well demonstrated that the nonlinear Schroedinger equation (NLS) describes the propagation of picosecond pulses in optical fibers [1,2]. However for femtosecond pulses this equation is no longer valid.

Methods, Assumptions and Procedures

We obtain conditions for femtosecond solitons which exhibit distinctions form the NLS using analytic methods. We find a requirement that both the second-order and third-order dispersion parameters be negative which rules out propagation in traditional graded-index fibers and necessitates the use of quadruple-clad fibers. Our starting point is the general equation describing the propagation of femtosecond pulses in dimensionless form

$$i\,q_z - \frac{1}{2} q_{tt} + |q|^2 q - i\,\varepsilon_1\, q_{ttt} + i\,\varepsilon_2\, |q|^2 q_t + i\,\varepsilon_3\, q^2\, q_t^* - \varepsilon_4\, |q|^2 q_t = 0 \qquad (1)$$

where $q = \sigma\left(\frac{n_2\omega_0}{c|\beta_2|}\right)^{1/2} A$, $z = \frac{|\beta_2|}{\sigma^2}\xi$, $t = \left(\tau - \frac{1}{v_g}\xi\right)\frac{1}{\sigma}$, $\varepsilon_1 = \frac{\beta_3}{6|\beta_2|\sigma}$,

$$\varepsilon_2 = \frac{2}{\sigma}\left(\frac{2}{\omega_0} + \frac{n'}{n} + \frac{3h'}{h}\right), \quad \varepsilon_3 = \frac{1}{\sigma}\left(\frac{2}{\omega_0} + \frac{n'}{n} + \frac{4h'}{h}\right), \quad \varepsilon_4 = \frac{T_R}{\sigma} ,$$

β_2 and β_3 are dispersion parameters given by the second and third derivatives of the propagation constant with respect to frequency, respectively, evaluated at the carrier frequency ω_0, n_2 is the nonlinear index of refraction, σ is the $\frac{1}{e}$ half-width of the pulse intensity, T_R is a parameter related to the slope of the Raman gain curve[3], n is the linear index of refraction, h is the frequency-dependent radius of the fiber mode, the primes denote the derivative with respect to frequency and the parameters are evaluated at ω_0, A is the slowly varying envelope of the electromagnetic field and the subscripts z and t refer to differentiation with respect to space and time, respectively. The parameter ε_1 describes the higher-order dispersion term, while ε_2 and ε_3 describe various aspects of self-steepening and ε_4 details the soliton self-frequency shift (SSFS). The SSFS is a continuous downshift of the mean frequency of the subpicosecond pulses. It has been explained in terms of the Raman effect through which the soliton can self-induce gain for the lower-frequency part of its spectrum at the expense of the higher-frequency part.[3]

Equation (1) reduces to the NLS for $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = \varepsilon_4 = 0$. However where $\varepsilon_3 = \varepsilon_4 = 0$ and $\varepsilon_1 = 6\,\varepsilon_2$, Eq. (1) gives rise to the expression

$$i\,q_z + \frac{1}{2} q_{tt} + |q|^2 q + i\,\varepsilon_1\,(q_{ttt} + 6|q|^2 q_t) = 0 \quad . \qquad (2)$$

The solution to Eq. (2) is given by [4]

$$q = q_0 \,\mathrm{sech}\left[q_0(t + \alpha z)\right] \exp\left[i(\mu t + \delta z)\right] \tag{3}$$

where
$$\alpha = 2\mu + \phi_0^2 \varepsilon_1 - 3\varepsilon_1 \mu^2$$
$$\delta = \phi_0^2 - \mu^2 - 3\varepsilon_1 \mu \phi_0^2 + \varepsilon_1 \mu^3 \quad .$$

Results and Discussions

One feature of this soliton is that its velocity differs from v_g by the parameter α which depends on the higher-order dispersion term, ε_1. The higher-order term ε_1 also affects the propagating phase of this soliton as can be seen from the parameter δ. The parameter μ is determined by the initial condition and physically corresponds to a frequency shift from the carrier frequency ω_0. It could be achieved experimentally through the use of an acousto-optic modulator. In principle, one can choose this parameter to be zero. However we have included it for the sake of generality. Equation (2) has bright soliton solutions [4], when both β_2 and β_3 are negative. This result necessitates using a quadruple-clad fiber rather than the typical graded-index fibers used in calculations and experiments to date. This realization is one significant feature of our results.

Intensity-dependent processes are of considerable interest as a means of *achieving* ultrahigh bit rates for optical communications or optical computing. The intensity-dependent refractive-index of silica fibers provides such a medium free of some of the problems associated with excitons or thermal nonlinearities found in semiconductors. Considerable effort has focused on nonlinear couplers in the picosecond domain [7–9] and soliton-like phenomena was observed in some cases. We expand this area of research to the femtosecond domain.

We have derived the coupled set of equations corresponding to Eq. (2) for a general case of nonlinear couplers, and we obtain [10]

$$i\,q_{1z} + \frac{1}{2}q_{1tt} + \left(|q_1|^2 + \gamma|q_2|^2\right)q_1 + k\,q_2$$
$$+\,i\,\varepsilon_1\left[q_{1ttt} + 3\left(|q_1|^2 + \gamma|q_2|^2\right)q_1 + 3\left(q_1^* q_{1t} + \gamma\, q_2^* q_{2t}\right)q_1\right] = 0$$
$$i\,q_{2z} + \frac{1}{2}q_{2tt} + \left(\gamma|q_1|^2 + |q_2|^2\right)q_2 + k\,q_1$$
$$+\,i\,\varepsilon_1\left[q_{2ttt} + 3\left(\gamma|q_1|^2 + |q_2|^2\right)q_{2t} + 3\left(\gamma\, q_1^* q_{1t} + q_2^* q_{2t}\right)q_2\right] = 0 \quad , \quad (4)$$

where k *is the linear cross-coupling term* and γ *is the* nonlinear cross-coupling parameter. For the nonlinear directional coupler, the nonlinear cross-phase modulation is negligible, therefore we set $\gamma = 0$.

Conclusions

In conclusion we present results for femtosecond all-optical switching whose novel features are encompassed through the use of quadruple-clad optical fibers rather than the traditional graded-index fibers. The wavelength region is restricted to ~ 1.48 to ~ 1.59 μm and pulse widths below 200 fs are required. These solitons differ from the traditional NLS in their velocity and phase.

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